Electric field induced charge noise in doped silicon: ionization of phosphorus donors

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We report low frequency charge noise measurement on silicon substrates with different phosphorus doping densities. The measurements are performed with aluminum single electron transistors (SETs) at millikelvin temperatures where the substrates are in the insulating regime. By measuring the SET Coulomb oscillations, we find a gate voltage dependent charge noise on the more heavily doped substrate. This charge noise, which is seen to have a 1/f spectrum, is attributed to the electric field induced tunneling of electrons from their phosphorus donor potentials.

With their high charge sensitivity single electron transistors (SETs) provide a valuable tool for investigating charge transport at the single electron level. These sensitive electrometers have been employed to directly observe electron traps in Al_2O_3 [1], and electron tunneling through GaAs quantum dots [2] amongst other systems. With particular relevance to this work, SETs have been used to study both time and frequency domain charge noise [3, 4, 5, 6] in semiconductor substrates. Charge noise in semiconductors has long been of interest [7], and recently has become an important issue for solid-state quantum computation where it is crucial that such noise is minimized to extend quantum coherence times.

We study the effect of electric fields on the charge noise in Si substrates with different doping levels. At millkelvin temperature the substrates are in the insulating regime ($n < n_{MIT} = 3.45 \times 10^{18} cm^{-3}$). For the intentionally doped substrate ($n = 8 \times 10^{16} cm^{-3}$) we find an additional 1/f charge noise on application of an electric field. By contrast, this charge noise was not measurable in the nominally intrinsic sample ($n = 1{\times}10^{14} cm^{-3}$). We therefore infer that its origin is electrons tunneling from their phosphorus donors [8, 9]. While this ionization effect can occur for both substrates, in the intentionally doped material a larger and more easily measurable charge redistribution is present due to the higher doping density.

Dopant ionization has previously been measured by transient currents due to the build-up of depletion regions in p-n junctions [10, 11], the slow formation of accumulation layers in MOS capacitors [12] and hysteretic effects in MOSFETs [13]. These experiments were mostly performed at an intermediate temperature range ($T = 4K - 20K$) where ionization can be thermally activated by the Poole-Frenkel effect [14]. At our experimental temperatures ($T \sim 100mK$), electric field assisted ionization is no longer dominated by thermal activation but is expected to be purely field assisted tunneling.

We fabricate the SETs using a standard bilayer resist and a shadow evaporation process. The electrostatic gate structure is evaporated Ti/Au and patterned in a separate electron beam lithography step (see fig. 1b inset). Both silicon substrates are terminated by 5nm of SiO_2 grown by thermal oxidization.

The SET conductance was measured using standard lock-in techniques at an excitation frequency of 1kHz and an amplitude of $20\mu V$. For the noise measurements a FFT analyzer was connected to the in-phase output of the lock in amplifier (LIA). Typically the range 0.244 Hz to 97.6 Hz was studied with a resolution bandwidth of 0.244 Hz. The sample was mounted in a dilution refrigerator with a base temperature of approximately 100mK and a 1T magnetic field was applied to suppress superconductivity in the SETs.

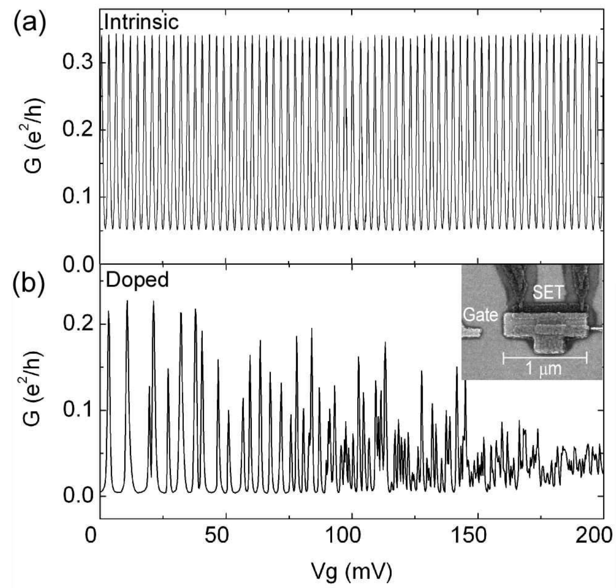

FIG. 1: a) Coulomb oscillations in the SET on the intrinsic substrate, showing no deviation from expected behavior. b) An identical measurement on the highly doped substrate. Contraction of the oscillation period and subsequent decay of the oscillations into noise is observed with increasing gate voltage.

Measurements of the SET fabricated on the intrinsic material (fig. 1a) show periodic Coulomb oscillations as a function of gate voltage. Little deviation from the periodicity is noticed over the voltage range swept and, in addition, there is no obvious change in the noise on the oscillations.

In the case of the doped substrate (fig. 1b), a significant departure from periodic charging occurs. Close to zero bias Coulomb oscillations are observed, then as the gate voltage is increased beyond 50mV, there is a con-

traction of the oscillation period and a reduction in oscillation visibility. Finally above some gate voltage, typically 150mV, the oscillations are completely suppressed and a constant, but noisy, conductance is measured. A similar effect is also experimentally observed for negative gate biases. This behavior is seen for a number of different devices made on this doped substrate, so rather than being device specific it is a general property of the material.

The gate voltage dependent charge noise increases with substrate doping density suggesting that the phosphorus donors are the source of the noise. Application of a gate

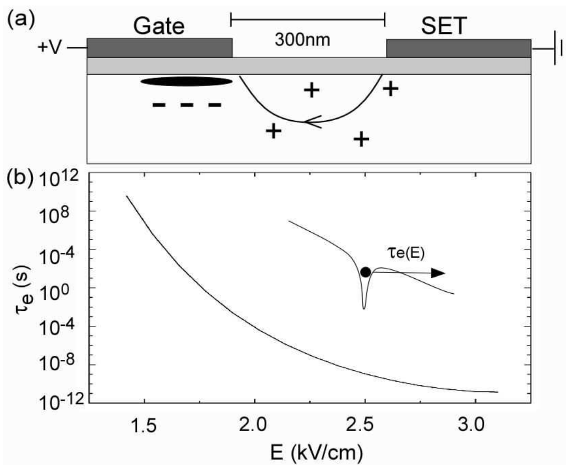

FIG. 2: a) For a positive gate voltage electrons are removed from the region of the SET and build up a layer of charge under the gate. b) The escape time for electrons bound to a Si:P donor on application of an electric field. This is calculated using a WKB approximation on a parabolic potential well. Inset showing a schematic of the tilted potential well.

voltage generates an electric field between the gate electrode and the SET defining the ground plane. It is known that if the electric field across a dopant is sufficiently large, electrons (holes) can tunnel from their confining potentials into the conduction (valance) band (fig. 2a inset). Following the method of a simple 1-D WKB approximation used to estimate the tunneling rate of holes from acceptors, we derive an estimate of the electron emission rate (fig. 2b) from phosphorus donors in an electric field [14].

For this device in which there is a 300nm gap between the gate and SET, electric fields in the region of 3kVcm^{-1} are achieved for an applied voltage of 100mV. At this value of electric field the electron lifetime is of the order 1ns. It can be seen that the electric fields applied during these measurements are sufficient to cause significant donor ionization.

The electric field is highest near the end of the gates and SET. Ionization therefore happens most rapidly in these regions. However, the electrons are mobile while the positively charged donors are not. Taking the gate voltage polarity as in fig 1., electrons that tunnel into the conduction band are accelerated towards the gate region where recombination with ionized donors is possible.

The net result is positively charged donors in the SET region and a layer of electronic charge at the Si-SiO_2 interface in the vicinity of the gate (fig. 2a). These positive charges are closer to the SET than the ionized electrons hence the SET sees a net additional positive potential. For low total ionization rates, this positive potential acts as an extra gate voltage. If this ionization rate increases with electric field then a period contraction will be observed. The complete loss of contrast in the Coulomb oscillations is consistent with a high level of charge noise.

Since P donors gradually ionize on application of an electric field, it is to be expected that the ionization noise is a non-equilibrium effect and has a time dependence. In order to investigate this time dependence, the charge noise was quantitatively studied using an FFT analyzer. In the measurement (fig. 3), the gate bias was ramped from zero to 300 mV over 30 mins, a gate voltage high enough to produce significant charge noise. This potential was maintained for 90 mins and finally ramped down to zero over 30 mins. At regular time intervals the noise spectrum between 0.244 Hz and 97.6 Hz was measured with the FFT analyzer. The lowest frequency measured here (0.24 Hz) corresponds to a time interval of 4s, and since 8 averages were taken this corresponds to a time of 32s. Since the noise doesn't change significantly over the measurement time, the noise measurement approximates one made on a stationary system.

Due to the magnitude of the charge noise experienced by the SET during these measurements it was not possible to keep the SET biased at the point of maximum charge sensitivity (halfway up a Coulomb oscillation). This accounts for the change in contrast between successive measurements.

As the gate voltage is increased from 0 mV to 300 mV a gradual increase in charge noise level occurs (fig. 3b). This is consistent with the observations of figure 1 and is because, at higher gate biases, more donors experience an electric field sufficient to cause ionization. In the second phase of the measurement, the gate potential is held constant for 90 minutes. Over this time there is reduction of the noise level (fig. 3c) but no return to the initial condition, presumably due to the long equilibration time at these low temperatures. A particular donor can ionize only once, so as the donors gradually ionize fewer events occur which can contribute to the charge noise. Eventually, on timescales longer than the present experiment, all available donors will have ionized and the charge noise returned to its initial value.

Finally, the gate voltage is lowered and almost immediately a reduction is observed in the noise level. This shows that the system did not reach equilibrium and can be explained by the sensitivity of tunneling rate on electric field. When the gate potential is reduced the electric field across the donors falls, and the escape rates for electrons still on donor sites decreases causing a sudden drop in charge noise in the substrate. Before the gate

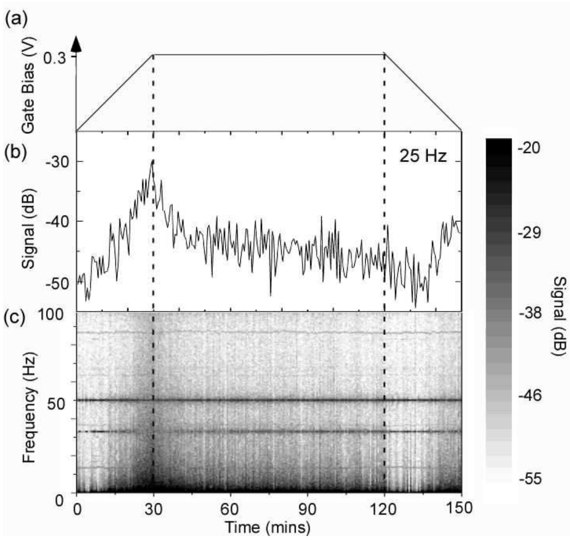

FIG. 3: a) Schematic of the voltage applied to the SET gate as a function of time. b) Charge noise measured in a bandwidth of 0.244 Hz around 25 Hz, showing the increase and subsequent equilibration of this noise. c) Charge noise for this voltage sequence applied to the highly doped substrate. The horizontal lines are due to mains noise.

voltage returns to zero bias, a further onset of charge noise occurs. This is likely to be recombination noise of the positively charged donors with the free electrons.

Donor ionization is a random, most likely Poissionian, process with a rate determined by the the electric field lowered tunnel barrier. The usual 1/f charge noise in semiconductors is often explained by an ensemble of two level fluctuators (TLF) having Lorentzian noise [15] distributions with different times constants. Donor ionization is a similar tunneling process to that in a TLF and hence also should yield a Lorentzian noise spectrum. In conventional noise models summing Lorentzians with different time constants gives a 1/f spectrum [7, 16] and hence a 1/f form would be expected here.

We measure noise spectra for different biasing conditions (fig. 4). Spectra are shown for biasing both in the trough and on the side of a Coulomb oscillation. The differences in noise magnitude here highlight the changing SET charge sensitivity [5]. Also shown is a measurement taken for a bias where ionization is occurring and the Coulomb oscillations have lost contrast, showing yet higher charge noise. All these spectra are close to 1/f, agreeing with the suggested model.

Using the SET as a charge detector we have measured electric field induced charge noise in insulating silicon substrates at low temperature. This noise, which depends on the doping density, is due to the ionization of electrons from their phosphorus donor potentials. Ionization of donors is of relevance to the noise properties of a wide range of semiconductor devices including semiconductor donor based quantum computers [17] where it determines the range of applicable gate voltages.

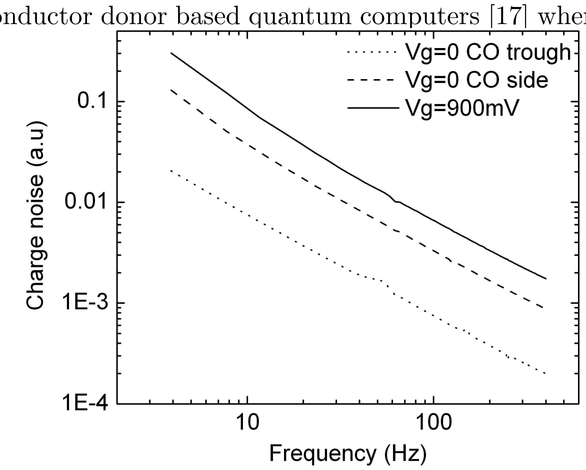

FIG. 4: Charge noise spectra measured in the absence and presence of significant ionization. In all cases the form is approximately 1/f. For the spectrum taken in the presence of ionization the dependence is $1/f^{1.04}$, a slight deviation is seen at the lower frequencies.

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